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# Comparing the techniques of defining the synchronous machine load angle

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**Abstract.** The low-frequency oscillations are natural for power systems and may arise due to both small variations of load and large disturbance. The effect of slight load changes may significantly differ for cases of low-magnitude permanent oscillations, which may be considered acceptable, and unstable oscillations, which may lead to a major system emergency. The existing trend of increasing the capacity of long-range power transmission has led to the situation where inter-area oscillations may appear underdamped or even rising in terms of magnitude. Effective oscillations detection with the corresponding countermeasures along with eliminating the prerequisites leading to the oscillations is a guarantee of minimizing their negative consequences. Therefore, it is of crucial importance to perform continuous monitoring which is to provide the information on the “source” of oscillations – a generator or a group of generators, which do not contribute to the oscillations damping or even support their development. The algorithm of quantitative estimation of synchronous generators participation in low-frequency oscillations damping based on synchronized phasor measurements has been proposed previously. It implies utilizing the concept of synchronizing power as a measure of the capability of the machine to maintain synchronous operation. The load angle of the generator is necessary to define the value of the synchronizing power and since the direct measurement of the load angle is generally not available the techniques of its derivation have been developed. The comparison of these techniques is presented with the estimation of the adopted assumptions effect on the synchronizing power evaluation results.

## 1. Introduction

Low-frequency oscillations (LFO) are one of the important problems faced in power system around the world. The oscillations jeopardize power systems’ reliability and stability, which leads to a significant decrease in transmission capacity. Therefore, the operation becomes less economic given the necessary levels of reliability and stability are ensured [1, 2].

The oscillations are naturally occurring in power systems and may result from minor load variations as well as disturbances such as generators or transmission lines trips. Large-scale centralized power systems interconnected by the weak tie-lines is a typical feature of the state-of-the-industry power engineering [3]. Another trend is distributed generation units integration with the resulting decrease of power system inertia constant and increasing sensitivity to small disturbances. In order to improve the controllability of power systems, modern equipment supplemented by fast-response control systems is introduced: asynchronized synchronous generators, FACTS (Flexible AC Transmission Systems), energy storage systems etc. Continuous changes in power system structure and parameters are other factors driving the LFO and threatening the equipment secure operation and the consumers power supply as well.

The resonance frequencies (eigen-frequencies) of the LFO in power systems fall within a range of 0.1÷3.0 Hz [4, 5]. The oscillations comprise local along with the inter-area ones, which may involve the whole power system. The local LFO characterize the mutual oscillatory movement of the synchronous machines within a power system region while the inter-area ones correspond to the mutual oscillations of the regions or machine groups against each other.

The analysis of power system state parameters often shows that there are time periods, within which the LFO damping is poor [6]. The presence of the underdamped oscillations means that the system operation may be unreliable due to the unpredictability of its dynamic response. Since all possible variations of operational conditions cannot be simulated using the dynamic model of a power system, the measurements-based monitoring of the LFO damping is crucial for preventing the potential threats before they may contribute to the development of a major emergency.

The LFO damping in power systems depends mostly upon control systems actions: automatic excitation and speed controllers, power system stabilizers [7], but may vary significantly subject to generators and load parameters and characteristics [8].

Ubiquitous introduction of Wide-Area Monitoring Systems (WAMS) based on the technology of synchronized phasor measurements provides the possibility to collect high-accuracy time-synchronized measurements of power system state parameters form Phasor Measurements Units (PMU) installed at power system entities. Moreover, advanced communication and data processing technologies allow to obtain these measurements “on-line” and to derive the LFO parameters, including frequency, magnitude and damping, on a real-time basis [9]. That said, the monitoring is to be performed not only during the transients or after the disturbances [10], but also during steady-state operation under normal conditions.

## 2. Estimation of synchronous generator participation in low-frequency oscillations damping

It is appropriate to adopt the quantity of power spent by the generator on the counteraction of the rotor slip relative to the system frequency as a measure of damping qualities of the generator [11]. This quantity is referred to as synchronizing power and the load angle is necessary to derive it. Three possible techniques of defining the load angle of a generator are described in detail in [12]. The selection of a technique follows a set of measured parameters with the measurements being based on on-site PMUs. The most accurate technique is obviously the one implying the load angle is directly measured mechanically by capturing the rotor angle and, optionally, angular velocity. In case the direct measurement is not possible, the load angle may be derived from the generator’s electric parameters with a number of assumptions being adopted [12].

Under the circumstances of the derived load angle uncertainty, which is driven by the assumptions made, the problem of assessing the said uncertainty is relevant. The main aim of the uncertainty assessment is defining the possible field of application for the derived load angle value and determining the necessity to equip the generators with the load angle measurement systems.

Since the estimation of synchronous generator participation in low-frequency oscillations damping based on the phasor measurements and the synchronous machine computational model depends significantly on the assumptions adopted for the simulation, it is appropriate and rational to perform assessment for actual generators or their physical models.

## 3. Comparing the results of defining the synchronous machine load angle

In order to compare the techniques of defining the synchronizing power of a synchronous machine operating in generator mode, the experiments have been carried out on a physical model of a nonsalient-pole generator. The generator under consideration is a component of the “Digital-analog-physical Complex” operated by the Scientific and Technical Center of the Unified Power System (STC UPS).

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The Digital-analog-physical complex includes the world's largest electrodynamic simulator (EDS) of electric power system (over 1000 models of physical generators, prime movers, transformers, transmission lines, complex load, direct current transmissions, FACTS, etc.) [13].

To implement the synchronizing power analysis algorithms, the EDS was equipped with the measurement system including the PMU capable of measuring the excitation parameters of a generator and the subsystem for measuring the rotor angle of a generator, comprising the magnet sensor and the tooth-wheel. The data obtained from the subsystem is recorded by the PMU as well. The measurement system was provided by Prosoft-Systems company [14], figure 1 shows the structure of the system. The fragment of the rotor angle measurement is presented in figure 2. The Prosoft-Systems SignW utility is employed for the raw data pre-processing. The electric parameters are derived from their instantaneous values of 10 kHz sampling rate in accordance with [15].

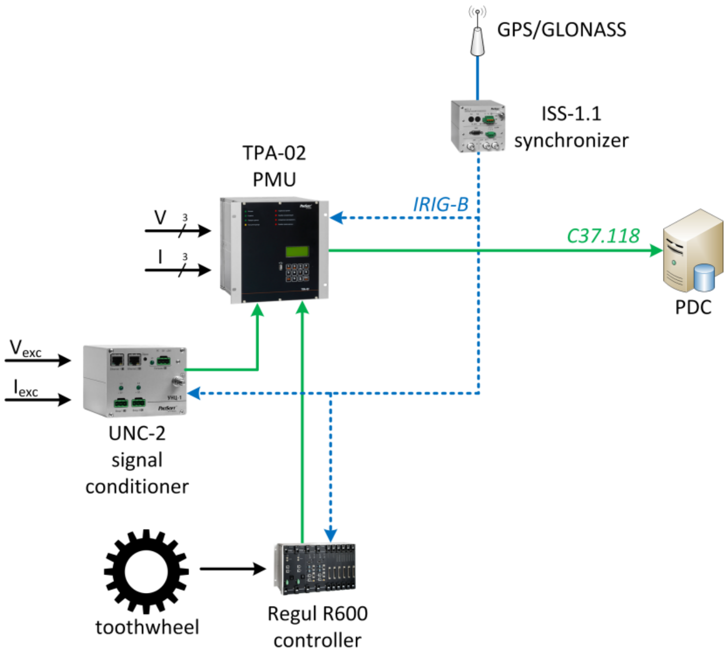


**Figure 1.** The structure of the measurement system.

The test data under consideration is the transient resulting from the load drop and surge represented by the corresponding changes of mechanical torque applied to the generator shaft. Figure 3 and figure 4 show the changes in generator's voltage frequency $f$ and active power $P_{em} = P_g$ [11].

The load angle and the synchronizing power of the generator during the considered LFO were derived by three techniques [12]. The stator resistance was neglected due to its small value. Figure 5 shows the load angle calculation results. One can see that the derived values differ from the results of the direct measurements. It also should be noted that the result of direct measurements may be further processed to obtain the smooth $\theta(t)$ curve.

Prior to the derivation of the load angle by using the technique 3 [12] the inductance of the machine $x$ is to be predefined with the value being refined according to the variations of frequency $f$. That said the predefined values may not correspond to the operational conditions preceding the disturbance. This disagreement may result in offsetting the derived values of the load angle. The following two values of the inductance were selected: the one derived experimentally on the basis of no-load and short-circuit characteristics of the machine ($x = x_d$) and the one derived on the basis of the directly measured load angle corresponding to the steady-state preceding the disturbance ($x = x_q$).

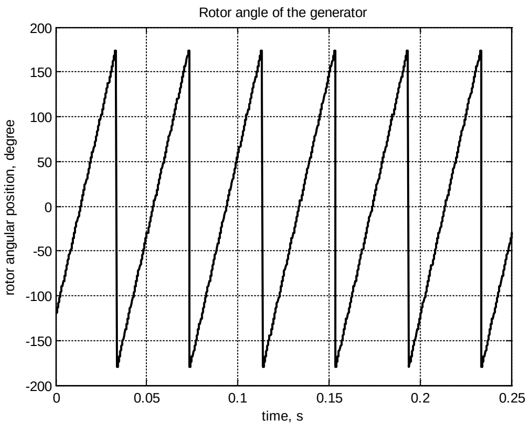


**Figure 2.** Rotor angle, degrees.

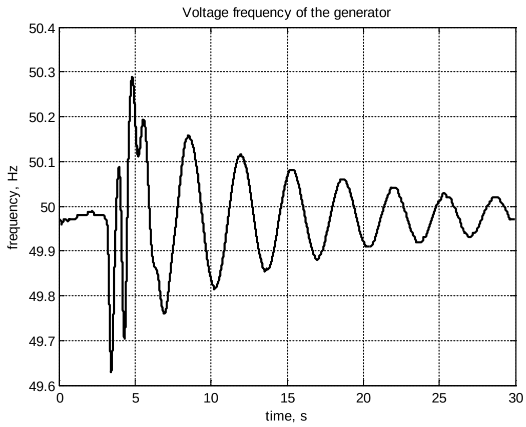


**Figure 3.** Voltage frequency $f$ of the generator, Hz.

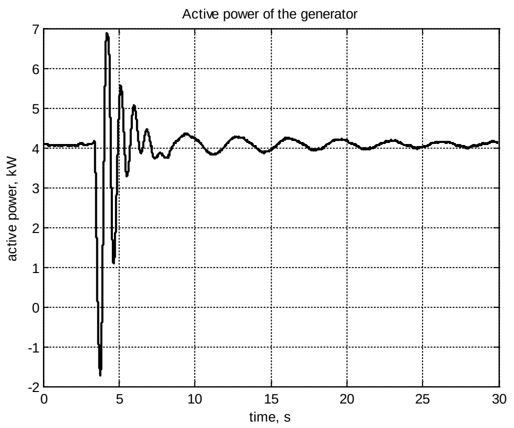


**Figure 4.** Active power of the generator, W.

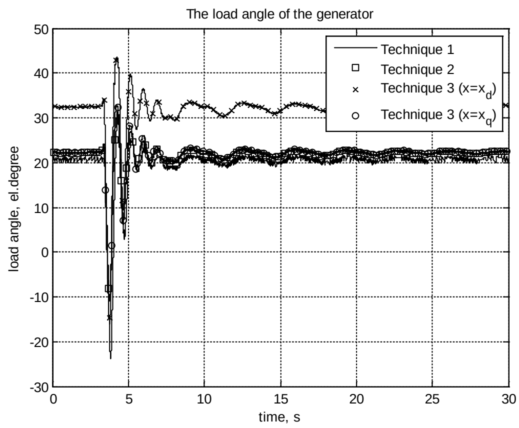


**Figure 5.** The load angle of the generator $\theta$, el. degrees.

It is not necessary to predefine the inductance value during the derivation by using the technique 2 [12] since the stator electro-motive force (EMF) is defined on the basis of no-load characteristic of the machine. The no-load characteristic is recorded in advance with the rotor rotation speed $\omega_r(t)$ and excitation current $I_f(t)$ being measured. Consequently, this technique is recommended for the analysis of small disturbances.

Under the described circumstances the technique 1 is the most preferable to be used, which implies that the load angle is defined on the basis of the rotor angle measurements. If that method is adopted, the results of the load angle defining are less dependent upon the condition of the generator's magnetic core. Adopting this technique allows to derive $P_s$ during either low-magnitude LFO or large disturbances.

The power-angle curve and the synchronizing power during the steady-state symmetrical operation may be defined according to the analytic formulas, developed under the assumption that the capacity of the system is infinitely larger than the capacity of the synchronous machine [11] given the state parameters and $x_d$, $x_q$ are known. Accordingly, the $P(\theta)$ and $P_s(\theta)$ will vary with the changes of the machine operational conditions. During the transient the ( $P(t), \theta(t)$ ) coordinates of the machine's operational point within $P-\theta$ axes are defined by the system conditions, the rotor's inertia constant, the machine's synchronizing and asynchronous damping torques and controllers' actions. Using the previously obtained results it is possible to plot the power-angle curve of the generator and its $P(t)$ against $\theta(t)$ trajectory. Figure 6 shows the $P(\theta)$ curve, corresponding to the steady-state prior to the disturbance, and the trajectory of the machine's operational point ( $P(t), \theta(t)$ ). The load angle $\theta(t)$ is obtained using the technique 1.

The synchronizing power $P_s(\theta)$ may be derived as "quasistatic" – the value of the specific synchronizing power, i.e. tangent tilt of $P(\theta)$ at current machine's operational point, corresponding to its operational conditions at current time instant $t$. The value characterizes the capability of the machine to maintain synchronous operation given the state parameters do not vary; the asynchronous damping torque of the machine and the controllers' actions are neglected.

The synchronizing power $P_s(t)$ during the transient was derived for the possible values of the load angle $\theta$ obtained according to the three techniques. Figure 7 shows the results – the synchronizing power $P_s(t)$ derived by the analytic formulas developed under the adopted assumptions.

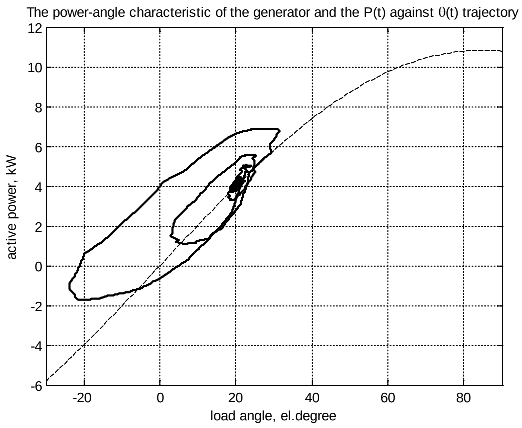


**Figure 6.** Power-angle curve $P(\theta)$ and the $P(t)$ against $\theta(t)$ trajectory.

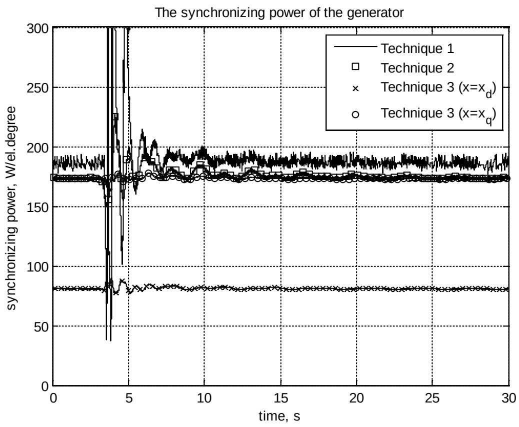


**Figure 7.** Synchronizing power of the generator $P_s(t)$, W/el. degree.

The alternative approach to calculation of the synchronizing power is numerical differentiation $\partial P(t)/\partial\theta(t)$. The direct differentiation allows to obtain the "dynamic" value of the synchronizing power $P_s(t)$ with consideration of the generator's rotor inertia constant, the changes in system operational conditions, the changes in the generator's voltage, voltage frequency and excitation current, the synchronizing and asynchronous damping torques of the machine and the actions of the controllers. Nonetheless, the result of the direct differentiation contains tangential discontinuities in the vicinity of the points where $\partial\theta \to 0$ and may turn out indefinite during quasi-steady-state operation, when $\begin{cases}\partial\theta \to 0 \\ \partial P \to 0\end{cases}$. Thus the further application of the obtained result is quite difficult. In order to obtain the practically applicable result the various numerical differentiation techniques may be employed.

## 4. Conclusion

The results of the carried out comparison for the considered physical model of a synchronous generator and the test disturbance may be summarized with the following conclusions.

- The considered techniques provide acceptable results.
- The most reliable one is the technique of the load angle defining on the basis of the rotor angle measurements. The computational methods may be employed in case the direct measurements

are missing, however their field of application is to be limited according to the errors resulting from the adopted assumptions.
- Estimation of a synchronous generator participation in the LFO damping on the basis of synchronizing power will improve the power system controllability and allow detecting the controllers' improper operation.

It is desirable to extend the comparative analysis of the load angle defining techniques involving the same physical model and different disturbances. It is of crucial importance to introduce as well the models comprising various generators and actual data obtained from power system entities.

The described methodology is expected to be implemented within the System of Power System Controllers Monitoring [16]. The main aim of the System is to detect in time the underdamped LFO and to define the source of the oscillations. At the time the algorithms of the System allow to identify the conventional faults of the excitation system of the generators: lack of or untimely excitation forcing, misoperation of the minimum/maximum excitation current limiter.

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